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The determination of the rotation period and magnetic field geometry of the strongly magnetic roAp star HD 154708*

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ABSTRACT

We obtained thirteen spectropolarimetric observations of the strongly magnetic rapidly oscillating Ap star HD 154708 over three months with the multi-mode instrument FORS 1, installed at the 8-m Kueyen telescope of the VLT. These observations have been used for the determination of the rotation period of $P = 5.3666 \pm 0.0007$ d. Using stellar fundamental parameters and the longitudinal magnetic field phase curve, we briefly discuss the magnetic field geometry. The star is observed nearly pole-on and the magnetic field geometry can be described by a centred dipole with a surface polar magnetic field strength $B_{\rm d}$ between 26.1 and 28.8 kG and an inclination of the magnetic axis to the rotation axis in the range 22.5° to 35.5°.

Key words: stars: magnetic fields - stars: chemically peculiar - stars: oscillations - techniques: polarimetric; individual: HD 154708

1 INTRODUCTION

The magnetic A and F stars have global magnetic fields with surface field strengths typically of a few kG to tens of kG. A subset of them, the rapidly oscillating Ap (roAp) stars, pulsate in high radial overtone magnetically distorted dipole and quadrupole modes with periods in the range $5.65 - 21$ min (see, e.g., Table 1 of Kurtz et al. 2006). These stars thus offer the opportunity to observe the interaction of p modes with strong magnetic fields as can be done for no other star but the sun. The kG-strength magnetic fields in sunspots dissipate energy in solar p-modes and shift their phases significantly, as is clearly seen in both observational and theoretical local helioseismology. While it is not possible to perform local asteroseismology in the same detail as for the sun – for obvious reasons of angular resolution – some unique properties of the roAp stars have the potential to allow 3D mapping of their pulsation modes, magnetic field geometries and abundance distributions within the observable layers of their atmospheres, hence allow a detailed study of the interaction of the pulsations with the magnetic fields.

The roAp stars with very strong magnetic fields are of special interest because the effect of the magnetic field on the structure of their atmospheres can be studied with the greatest detail and accuracy. The cool roAp star HD 154708 possesses the strongest magnetic field among the roAp stars, with a mean magnetic field modulus $\langle B \rangle = 24.5 \pm 1.0$ kG (Hubrig et al. 2005), which is about a factor of three greater than that of HD 166473, $\langle B \rangle \sim 5.5$–9.0 kG (Mathys, Kurtz, & Elkin 2007), the roAp star with the second-strongest magnetic field. For all of the roAp stars the pulsations observed in radial velocity variations of lines of the rare earth elements arise at atmospheric heights where the magnetic pressure exceeds the gas pressure and the Alfvén velocity is greater than the acoustic velocity, so the pulsations are primarily magnetic with an acoustic component. There have been many theoretical investigations of the roAp stars discussing, e.g., mode conversion and reflection, contributions of horizontal and vertical motions to the observed pulsational radial velocities, and mode excitation and suppression in these stars (see, e.g., Sousa & Cunha 2008 and Saio 2005, and references therein).

All of the theoretical models are for atmospheres with magnetic field strengths less than 10 kG. Thus the discovery

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of pulsation in HD 154708 in the presence of its 24.5-kG field charts new territory. With its field strength more than 15 times the 1.5 kG typically observed in sunspots, HD 154708 by far shows the most extreme observable case of pulsation in the presence of a strong magnetic field (Kurtz et al. 2006). We thus wish to know as much about it as possible, and for obliquely rotating and pulsating Ap stars it is imperative to determine their rotation periods and magnetic variations with rotation to extract important geometrical information.

The atmospheric parameters of HD 154708, $T_{\rm eff}$ = 6800 K and $\log g$ = 4.11, have been determined using the B2−G temperature calibration of Geneva photometry (Hauck & North 1993, Eqn. 2) and the Hipparcos parallax (Hubrig et al. 2005); Strömgren photometry (Napiwotzki, Schoenberner, & Wenske 1993) suggests a hotter temperature, $T_{\rm eff}$ = 7500 K. The magnetic field in this star was discovered during our systematic study of magnetic fields in chemically peculiar Ap and Bp stars with the multimode instrument FORS 1 installed at the 8-m Kueyen telescope (Hubrig et al. 2005). Among the whole class of Ap and Bp stars, the only star known at that time to have a stronger dipolar magnetic field than HD 154708 was the much hotter ($T_{\rm eff}$ ≈14 500 K; Leckrone 1974) Bp Si star HD 215441 (Babcock's star) with a mean field modulus of $\langle B \rangle = 34$ kG (Babcock 1960). Now Freyhammer et al. (2008) have found a field of $\langle B \rangle = 30.29 \pm 0.08$ kG in HD 75049, making this the second-strongest dipolar field known among the upper main sequence chemically peculiar stars.

The presence of pulsations with a period of 8 min was discovered by Kurtz et al. (2006) using 2.5 h of high time resolution UVES (Ultraviolet and Visual Echelle Spectrograph) spectra. They found that the radial velocity amplitudes in the rare earth element lines of Nd II, Nd III, and Pr III were unusually low, suggesting that roAp stars with stronger magnetic fields have lower pulsation amplitudes. Further study of the pulsation of HD 154708 over its now-known 5.3666-d rotation cycle will illuminate this suggestion, as would theoretical studies of models with field strengths up to 30 kG.

A recent abundance analysis of HD 154708 was based on a high spectral resolution UVES spectrum obtained on September 18, 2005 (Nesvacil, Hubrig, & Khan 2008). The atmospheric chemical composition of this star was shown to be typical of cool Ap stars with a significant ionization disequilibrium for the first and second rare earth ions, which is commonly observed in the atmospheres of pulsating roAp stars (Ryabchikova et al. 2004). The model atmosphere was calculated with the LLModels code (Shulyak et al. 2004). Light elements, as well as Ti, Fe, and Ni were found underabundant whereas Sc and Cr showed solar abundances. Heavy elements and rare earth elements were strongly overabundant. Nd III is 0.86 dex overabundant with respect to Nd II and Pr III was overabundant by 1.11 dex compared to Pr II.

Cowley et al. (2007) studied the presence of heavy Ca isotopes in HD 154708 using the infrared triplet lines of Ca II. They measured isotopic shifts of +0.14 Å, +0.26 Å, and +0.29 Å for λ8498, 8542, and 8662, respectively. However, the maximum isotopic shifts between the isotopes ^{40}Ca and ^{48}Ca for the Ca II triplet lines is of the order of 0.2 Å. Possibly these differences are caused by other effects than isotopic shifts – most likely, blending with highly displaced Zeeman components. The magnetic field of HD 154708 is so strong that a number of spectral lines are distorted beyond recognition by the partial Paschen-Back effect.

Table 1. Magnetic field measurements of HD 154708 with FORS 1. All quoted errors are 1σ uncertainties. In the last three lines we list the earlier measurements published in Hubrig et al. (2006).

MJD	$\langle B_{\rm z}\rangle_{\rm all}$ [G]	$\langle B_{\rm z}\rangle_{\rm hydr}$ [G]
54209.3072	7941±15	7711±41
54215.2792	7557±15	7301±49
54223.1734	6765±15	6174±41
54238.2840	6427±23	6062±65
54247.1726	7726±20	7483±62
54254.1219	6497±28	6103±80
54258.2500	7462±20	7330±59
54270.3097	6479±15	6169±46
54279.1667	7884±15	7710±44
54287.2260	6326±59	5718±169
54297.3028	6450±28	6211±83
54305.1536	7873±18	7492±49
54307.0214	7032±18	6884±41
53120.376		7530±54
53487.302		5764±25
53519.344		5819±52

The magnetic field geometry in HD 154708 has not previously been studied. In this work we present for the first time a mean longitudinal magnetic field measurement series, obtained with the multi-mode instrument FORS 1 installed at the 8-m Kueyen telescope. The data are used to obtain the rotation period and to put constraints on the magnetic field geometry. This is the first, necessary step for a more detailed study of this remarkable star.

2 OBSERVATIONS

The observations were carried out in 2007 April – July in service mode. Using the narrowest available slit width of 0.″4 the achieved spectral resolving power of the FORS 1 spectra obtained with the GRISM 600B was about 2000. These observations made use of a new mosaic detector with blue optimized E2V chips, which was installed in FORS 1 at the beginning of April 2007. It has a pixel size of 15 μm (compared to 24 μm for the previous Tektronix chip) and higher efficiency in the wavelength range below 6000 Å. With the new mosaic detector and the GRISM 600B, we are also able to cover a much larger spectral range, from 3250 to 6215 Å. A detailed description of the assessment of the longitudinal magnetic field measurements using FORS 1 is presented in our previous papers (e.g., Hubrig et al. 2004a,b, and references therein). We repeat here the major steps of the magnetic field determination. The mean longitudinal magnetic field, $\langle B_{\rm z}\rangle$, was derived using

$$\frac{V}{I} = -\frac{g_{\rm eff} e \lambda^2}{4\pi m_e c^2}\ \frac{1}{I}\ \frac{{\rm d}I}{{\rm d}\lambda}\ \langle B_{\rm z}\rangle\,, \qquad (1)$$

where V is the Stokes parameter which measures the circular polarization, I is the intensity in the unpolarized spectrum, $g_{\rm eff}$ is the effective Landé factor, e is the electron charge, λ is

the wavelength, m_e the electron mass, c the speed of light, $\mathrm{d}I/\mathrm{d}\lambda$ is the derivative of Stokes I, and $\langle B_\mathrm{z}\rangle$ is the mean longitudinal magnetic field. To minimize the cross-talk effect, we executed a sequence of spectropolarimetric observations at different position angles of the retarder waveplate, +45−45, +45−45, +45−45, etc., and calculated the values V/I using:

$$\frac{V}{I} = \frac{1}{2}\left\{ \left(\frac{f^\mathrm{o} - f^\mathrm{e}}{f^\mathrm{o} + f^\mathrm{e}}\right)_{\alpha=-45^\circ} - \left(\frac{f^\mathrm{o} - f^\mathrm{e}}{f^\mathrm{o} + f^\mathrm{e}}\right)_{\alpha=+45^\circ} \right\}, \quad (2)$$

where α denotes the position angle of the retarder waveplate and f^o and f^e are ordinary and extraordinary beams, respectively. Stokes I values were obtained from the sum of the ordinary and extraordinary beams. To derive $\langle B_\mathrm{z}\rangle$, a least-squares technique was used to minimize the expression

$$\chi^2 = \sum_i \frac{(y_i - \langle B_\mathrm{z}\rangle x_i - b)^2}{\sigma_i^2} \quad (3)$$

where, for each spectral point i, $y_i = (V/I)_i$, $x_i = -\frac{g_\mathrm{eff} e \lambda_i^2}{4\pi m_e c^2}$ $(1/I \times \mathrm{d}I/\mathrm{d}\lambda)_i$, and b is a constant term that, assuming that Eq. 1 is correct, approximates the fraction of instrumental polarization not removed after the application of Eq. 2 to the observations. In our calculations we assumed a Landé factor $g_\mathrm{eff} = 1$ for hydrogen lines and $g_\mathrm{eff} = 1.25$ for metal lines. The average Landé factor for metal lines is obtained using individual Landé factors for the observed spectral lines and is close to the value $g_\mathrm{eff} = 1.23$ published by Romanyuk (1984). Furthermore, in our reduction procedure the spectral regions containing telluric lines have been excluded in the measurements of the magnetic field. The errors of the measurements of the polarization have been determined from photon statistics and have been converted to errors of field measurements. Longitudinal magnetic fields were measured in two ways: using only the absorption hydrogen Balmer lines, or using the entire spectrum including all available absorption lines. Due to the low resolution of the FORS1 polarimetric spectra and due to the fact that the major contribution to the measured magnetic field strength comes from the hydrogen lines, the weak-field approximation can be reasonably adopted for magnetic field strengths up to a few tens of kG. The results of our magnetic field measurements are presented in Table 1. In the first column we provide the modified Julian dates at the middle of the exposures. The measured mean longitudinal magnetic field $\langle B_\mathrm{z}\rangle$ using the whole spectrum is presented in Col. 2. The measured mean longitudinal magnetic field $\langle B_\mathrm{z}\rangle$ using all hydrogen lines is listed in Col. 3. All quoted errors are 1σ uncertainties. In the last three lines we list the earlier measurements published in Hubrig et al. (2006).

3 PERIOD DETERMINATION

An initial frequency analysis was performed on the longitudinal magnetic field measurements given in Col. 2 of Table 1 using the discrete Fourier transform programme of Kurtz (1985). The resulting amplitude spectrum clearly shows a dominant peak with an equivalent period near 5.3 d, but the 13 measurements are not uniformly sampled over the rotation cycle for this period. We thus used the more appropriate frequency analysis technique of fitting a sinusoid by linear least-squares for a range of frequencies. Fig. 1 shows the unambiguous result. The best-fitting frequency of $0.18627\,\mathrm{d}^{-1}$ was then fitted by both linear least-squares and nonlinear least-squares sinusoidal fitting routines. The latter allows an estimate of the frequency uncertainty, and the former gives estimates of the amplitude and phase error of the fit. The resulting best fit gives the rotational frequency $f_\mathrm{rot} = 0.1863 \pm 0.0007\,\mathrm{d}^{-1}$, for a rotational period of $P_\mathrm{rot} = 5.367 \pm 0.020$ d. The derived ephemeris for this period is:

$$\langle B_\mathrm{z}\rangle^\mathrm{max} = \mathrm{MJD}54257.26 \pm 0.03 + 5.367 \pm 0.020E \quad (4)$$

To refine the period determination we combined the data in Col. 3 of Table 1 for the hydrogen lines with three previously published measurements made using the same technique obtained by Hubrig et al. (2006). This data set has a time span of 3 y, hence higher frequency resolution than the frequency analysis of the data obtained in a single season presented in Fig. 1. However, with only a few data points from previous years, the alias problem must be examined carefully. Because of the sparse distribution of the data, a frequency analysis was performed by fitting sinusoids by least-squares over an appropriate range of frequencies. As can be seen in Fig. 2, there is some alias ambiguity, but it is not severe and a best-fitting frequency can be selected. As long as this is the correct alias, the rotation period is therefore refined to $P_\mathrm{rot} = 5.366 \pm 0.002$ d for HD 154708. For this determination equal weights were used. To increase the accuracy of the rotation period even further, we used a non-linear least-squares fit of the function $\overline{\langle B_\mathrm{z}\rangle} + A_{\langle B_\mathrm{z}\rangle} cos(2\pi(t/P + \phi))$ to the same 16 data points with weights equal to $1/\sigma^2$, with the 1σ uncertainties as listed in Col. 3 of Table 1. We used the value $P = 5.366$ found as the starting value for the fit and find $P_\mathrm{rot} = 5.3666 \pm 0.0007$ d. We consider this rotation period as the most accurate. A similar fit was performed on the 13 data points obtained using the entire spectrum including all available absorption lines, but we kept in this case the period fixed. The resulting final values are $\overline{\langle B_\mathrm{z}\rangle} = 7199 \pm 11$, $A_{\langle B_\mathrm{z}\rangle} = 789 \pm 13$ and $\phi = 0.774 \pm 0.003$ with a reduced $\chi^2 = 3.6$. This implies for the derived ephemeris for the maximum value of the magnetic field:

$$\langle B_\mathrm{z}\rangle^\mathrm{max} = \mathrm{MJD}54257.24 \pm 0.02 + 5.3666 \pm 0.0007E \quad (5)$$

where the reference date is at the maximum closest to the middle of the observations presented in this paper.

The corresponding phase diagram, including the best sinusoidal fit, is shown in Fig. 3, along with the residuals (lower panel). Note that the size of the error bars is comparable to the size of the dots representing the individual measurements. The scatter of the latter about the best-fit curve is also of the same order: this is a strong indication that the 1σ uncertainties given in Table 1 are good estimates of the actual random errors of the measurements (Landstreet 1980). To our knowledge, the present data represent the first set of mean longitudinal magnetic field measurements of a single star obtained with FORS 1 with a sufficiently uniform phase coverage to establish this important result. The measurement with the largest sigma ($\langle B_\mathrm{z}\rangle_\mathrm{all} = 6326 \pm 59$ G) was obtained in weather conditions classified as "thick clouds", where the guide star was frequently lost, and thus was repeated by the service observer a couple of nights later. With-

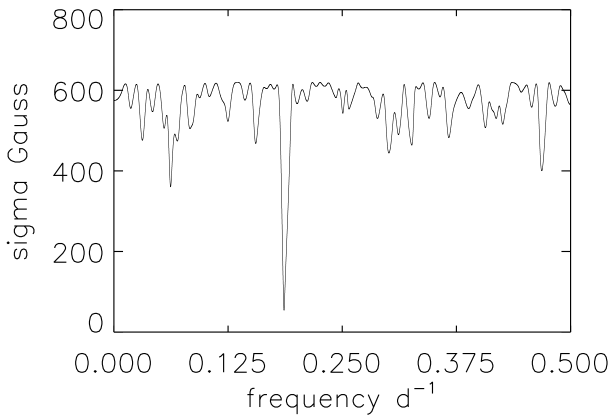

Figure 1. For the data in Col. 2 of Table 1, this plot shows the standard deviation of one measurement with respect to a sinusoidal fit for a range of frequencies. There is a clear best fit for a frequency of $0.1863\,\mathrm{d}^{-1}$, or $P = 5.367$ d.

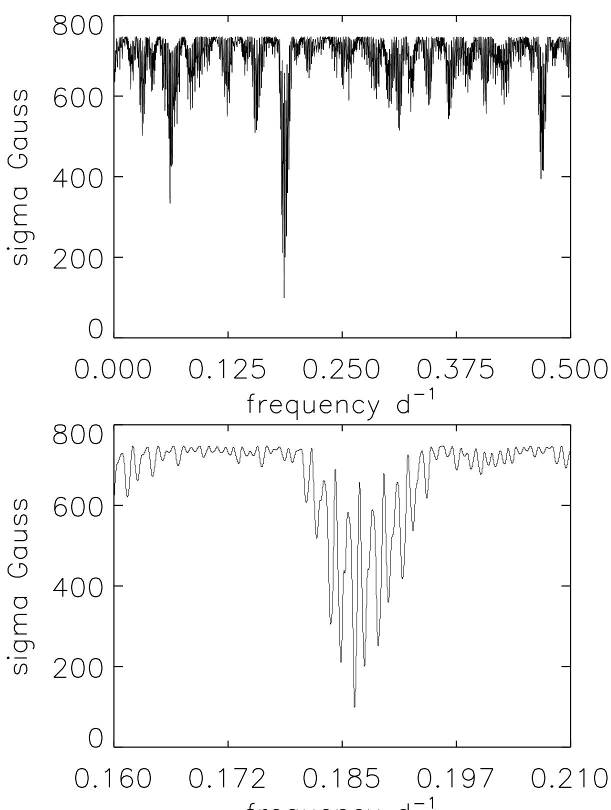

Figure 2. For the data in Col. 3 of Table 1, plus three previously published measurements of the magnetic field of HD 154708 for the hydrogen lines, these plots show the standard deviation of one measurement with respect to a sinusoidal fit for a range of frequencies. The top panel shows that the best-fitting frequency is close to that determined in Fig. 1, and the bottom panel shows at higher resolution that there is a best-fitting frequency with some alias ambiguities that fit less well. The best-fitting frequency is $f_{\mathrm{rot}} = 0.18635 \pm 0.00008\,\mathrm{d}^{-1}$, or $P_{\mathrm{rot}} = 5.367 \pm 0.002$ d. A weighted nonlinear least squares fit finally gives $P_{\mathrm{rot}} = 5.3666 \pm 0.0007$ d (see eq. 5) and discussion in the text.

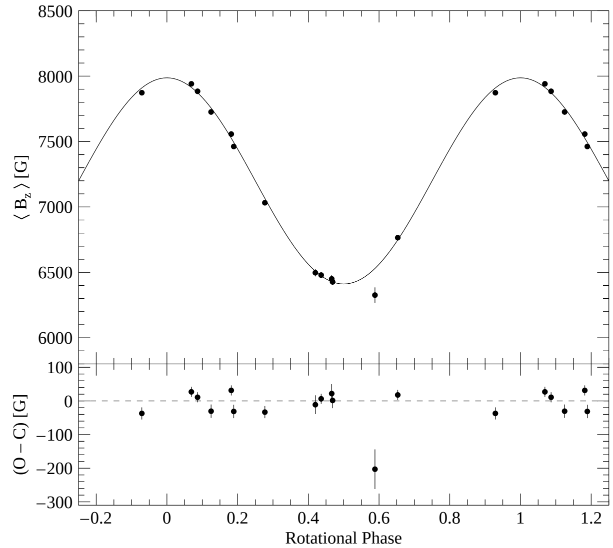

Figure 3. Phase diagram for the magnetic field measurements using all lines (Col. 2 of Table 1) for the **m**ost most accurate period, $P_{\mathrm{rot}} = 5.366$ d. The variation has a mean of $\overline{\langle B_{\mathrm{z}} \rangle} = 7199 \pm 11$ G and an amplitude of $A_{\langle B_{\mathrm{z}} \rangle} = 789 \pm 13$ G. The residuals (Observed – Calculated) for the best fit is shown in the lower panel. The deviations are mostly of the same order as the error bars, and no systematic trends are obvious, which justifies a single sinusoid as a fit function. For the point near phase 0.6, see text.

out taking into account this measurement we obtain a reduced $\chi^2 = 2.6$.

4 DISCUSSION

A rather short rotation period of 5.3666 days is obtained for HD 154708 based on the new thirteen low resolution spectropolarimetric observations. This is fully consistent with the result found by Mathys et al. (1997) that mean magnetic field moduli in excess of 7.5 kG are only found in stars with rotation periods shorter than 150 days. While many magnetic Ap stars have very long rotation periods, up to several tens of years, or even close to 1 century in some cases, none of them have extremely strong fields such as HD 154708.

Hubrig et al. (2005) found for HD 154708 a very low value for $v \sin i$. Our recent fit to the observed spectral line profile of the magnetically insensitive line Fe I λ 5434.5 resulted in $v \sin i = 3.5 \pm 0.5\,\mathrm{km\,s^{-1}}$. This is consistent with the value of $4\,\mathrm{km\,s^{-1}}$ obtained by Elkin, Kurtz, & Mathys (2008).

Knowing the position of the star in the H-R diagram (Hubrig et al. 2005), we determine the radius of the star to be in the range $R = 1.7 - 2.0\,\mathrm{R}_{\odot}$. The equatorial rotation velocity is given by $v_{\mathrm{eq}} = 50.6 R/P$, where R is the stellar radius in solar units and P the period in days. From the measured $v \sin i$ values and v_{eq} determined using the known rotation period and the radius computed from the luminosity and effective temperature, the inclination of the stellar rotation axis of HD 154708 can be determined. We obtain $v_{\mathrm{eq}} = 16 - 18.9\,\mathrm{km\,s^{-1}}$, leading to a value for the inclination angle in the range $i = 9^{\circ} - 14.5^{\circ}$.

Our measurements exhibit a smooth, single-wave variation of the longitudinal magnetic field during the stellar

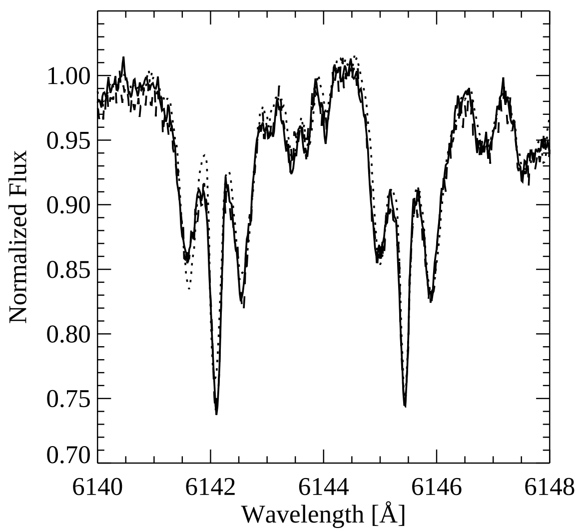

Figure 4. One spectrum of HD 154708 was obtained on May 20, 2005 at phase 0.72 and is indicated by the solid line. The second spectrum was observed on September 18, 2005 at phase 0.37 and is presented by the dotted line. The third spectrum was observed on July 23, 2006 at phase 0.76 and is presented by the dashed line. No obvious changes are detectable in the split Zeeman structure of the presented spectral lines.

rotation cycle. These observations can be considered as evidence for a dominant dipolar contribution to the magnetic field topology. Based on the assumption that the magnetic Ap stars are oblique dipole rotators, Preston (1967) defined

$$r = \frac{\langle B_\mathrm{z}\rangle^{\min}}{\langle B_\mathrm{z}\rangle^{\max}} = \frac{\cos\beta\cos i - \sin\beta\sin i}{\cos\beta\cos i + \sin\beta\sin i}, \tag{6}$$

so that the obliquity angle, β is given by

$$\beta = \arctan\left[\left(\frac{1-r}{1+r}\right)\cot i\right]. \tag{7}$$

From the values determined above, $\langle B_\mathrm{z}\rangle^{\max} = 7988 \pm 17$ G and $\langle B_\mathrm{z}\rangle^{\min} = 6410 \pm 17$ G, we find $r = 0.802 \pm 0.004$, which for $i = 9^\circ - 14.5^\circ$ leads to a magnetic obliquity in the range of $\beta = 22.5^\circ - 35.5^\circ$. This value is close to the low end of the range of obliquities determined by Landstreet & Mathys (2000) for magnetic Ap stars with rotation periods shorter than 25 days.

For a tilted, centred magnetic dipole and assuming a limb darkening parameter of $u = 0.5$, the surface polar field strength B_d is $B_\mathrm{d} \geqslant 3.23\,\langle B_\mathrm{z}\rangle^{\max}$ (Preston 1967), i.e. $B_\mathrm{d} \geqslant 25.8$ kG for HD 154708. Using the values determined for i and β, we find B_d=26.1 kG for i=9° and β=35.5° and B_d=28.8 kG for i=14.5° and β=22.5°. The measured magnetic field modulus of ∼24.5 kG using magnetically resolved lines (Hubrig et al. 2005) is of the same order as that estimated for the presented geometry of the magnetic field.

The limb-darkening coefficient is a function of wavelength. Since no realistic model atmosphere exists yet for the roAp stars with extremely strong magnetic fields, the actual mean limb-darkening coefficient for the spectral range we observed for HD 154708 is uncertain. We note that the choice of other mean limb-darkening coefficients would extend the range of possible B_d values.

The high spectral resolution UVES spectra of HD 154708 at three different dates at a resolving power of $\lambda/\Delta\lambda \approx 1.1 \times 10^5$ available in the ESO archive show almost the same appearance of magnetically resolved Zeeman components. In Fig. 4 we present these three spectra where no significant changes in the split line structures is visible, indicating no noticeable change in the magnetic field modulus between these effectively two rotation phases (since two of the spectra happen to be at nearly the same rotation phase). The spectra obtained on May 20, 2005 at phase 0.72 and on July 23, 2006 at phase 0.76 are average spectra of the time series used to study rapid oscillations in this star. This does not represent a strong constraint: in more than half of the known Ap stars with resolved magnetically split lines, the ratio between the extrema of the mean field modulus is lower than 1.1, and in 75% of them, it does not exceed 1.3. The three measurements of $\langle B\rangle$ that are currently available are insufficient to define its variation, or to check its consistency with the derived value of the rotation period.

Landstreet & Mathys (2000) found a predominance of small values of β for stars with $P_\mathrm{rot} > 25$ d. The only star with a comparable field strength in their sample is Babcock's star HD 215441, which has i and β angles of the order of ∼30°, i.e. similar to the i and β determined for HD 154708. Babcock's star is much hotter and more massive than HD 154708, and its rotation period is somewhat longer at ($P_\mathrm{rot} = 9.5$ d) than that of HD 154708. It is premature to make any statistical assertion about the efficiency of magnetic braking and field geometry evolution just from the knowledge of these two strongly magnetic stars. On the other hand, Hubrig, North, & Schöller (2007) studied the behaviour of the angle β in Ap stars of different masses and ages. The obliquity angle distribution as inferred from the distribution of r-values appears random at the time magnetic stars become observable on the H-R diagram. After only a short time spent on the main sequence, the obliquity angle β then tends to reach values close to either 90° or 0° for $\mathrm{M} < 3\,\mathrm{M}_\odot$.

As we already mentioned above, due to the presence of the very strong magnetic field in the atmosphere of HD 154708, its spectrum is very complex and many spectral lines need a detailed Paschen-Back treatment. On the other hand, due to the low value of $v\sin i$ and the relatively short rotation period, this star is one of the most suitable targets to study various atmospheric effects that interact with a strong magnetic field.

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